

BIODIVERSITY-BASED PROPOSITIONS OF CONSERVATION AREAS IN BAA ATOLL, REPUBLIC OF MALDIVES

BY

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ABSTRACT

The Republic of Maldives is an atoll country entirely composed of coral reefs and is vulnerable to the many threats that may impair the resilience of coral reefs. Ongoing projects aim to enhance scientific knowledge of Maldives ecosystems and promote conservation. As a contribution to the Atoll Ecosystem Conservation project (AEC) focused on Baa Atoll, we identified high priority conservation areas using a unique biodiversity dataset (macrophytes, coral, fish, hydrozoans and other select macro-invertebrates census) and detailed habitat maps derived from Landsat and Quickbird satellite imagery. Species richness and distribution were mapped across the atoll and used by sitting algorithms to identify areas of high priority for biodiversity conservation. Algorithms were parameterized with the ConsNet software to meet species representation criteria within a conservation area network as compact as possible. These are conceptually simple classical designs, but they remain surprisingly seldom applied in coral reef conservation management. The design led in Baa to conservation choices likely to be accepted by Maldivian stakeholders. Indeed the recommendations are consistent with parallel AEC recommendations made according to charismatic mega-fauna distribution and tourism industry interests. The Baa Atoll example provides an illustrated step-by-step conservation planning procedure that can be easily replicated elsewhere.

INTRODUCTION

The Republic of Maldives consists entirely of coral reefs, the most diverse of all marine ecosystems. Maldives includes 26 geographical atolls, composed of approximately 1,190 individual coral structures (islands, *faro*, patches and knolls) (Hoon et al., 1997). The increasing local population is concentrated on only a few reef-islands and a growing number of resort-islands accommodate tourists in most atolls. In the past decades, coral reefs and marine biodiversity in general have driven economic incomes through fishing and tourism. Population growth and hotel construction increased both demand for sand and coral mining, and also levels of reef fishing (Sattar et al., this issue). Climate change is also a severe threat, mainly characterized by bleaching events such as in 1998 (Wilkinson et al., 1999), and sea level rise.

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The Maldivian government, recognizing the value of coral reefs for the tourism industry (Environment Protection and Preservation Act of Maldives 4/93), established 15 Marine Protected Areas (MPAs) in 1995, followed by 10 more in 1999. One more was implemented in 2007 and more recently, three MPAs were established in 2009. Today, the Maldives have 29 MPAs spread across 12 atolls, but most implementation decisions have been made on an *ad hoc* basis, principally driven by popularity as dive sites and without preliminary site characterization. Recently, the Government of Maldives together with the United Nations Development Program (UNDP) and Global Environment Facility (GEF) launched the Atoll Ecosystem Conservation Project (AEC) (www.biodiversity.mv/aec, (AEC, 2009b, a)). The purpose of this project is to design an effective management system for atoll ecosystem conservation and sustainable development (AEC, 2009a). Baa Atoll (also called *South Maalhosmadulu Atoll*) was the pilot atoll selected to conduct the AEC project. The atoll was recently recognized as a UNESCO Biosphere Reserve in 2011.

Part of the AEC task is also to establish new MPAs in Baa Atoll, based on clearly established conservation targets and supported by adequate data collection. AEC has conducted rapid surveys for this purpose (Le Berre et al., 2009) and designed a conservation plan focused on indicator species (e.g. megafauna like whale sharks, manta rays and sea turtles) and ecosystems.

Our project contributes to the AEC project by proposing alternative MPA solutions using a new biodiversity dataset specifically collected for this purpose. The biodiversity dataset includes species lists for macrophytes (Payri and Mattio, this issue), corals (Bigot and Hamir, this issue), fish (Chabanet et al., this issue), hydrozoans (Gravier-Bonnet and Bourmaud, this issue), other select macro-invertebrates (select classes of Cnidaria, Echinodermata, Mollusca, Porifera, Chordata, Plathelminthes, and Annelida, Andréfouët et al., this issue, a), and habitat maps (Andréfouët et al., this issue, b). These datasets allow inserting in a two dimensions spatially-explicit framework (the habitat maps), the multi-taxa points of biodiversity census.

We report here on the strategy followed to locate areas of high conservation priority using this biodiversity dataset, in order to meet species representation conservation criteria. The proposed networks of MPAs can be used by AEC and other stakeholders as a first objective basis for biodiversity conservation, and to feed more holistic conservation planning strategy based on criteria of different nature (e.g socio-economy, climate change or resilience).

METHODS

Study Area

Baa Atoll (Fig. 1) is the focus of the AEC project. It comprises 75 individual reef and *faro* for a total area of approximately 1200 km². Ten islands are inhabited, with a combined population of approximately 11000 people. Thus far, six islands have been developed as resorts and new projects are planned. While resorts have become the main

economic driver, tuna and reef fishing remains an important activity on Baa Atoll (Sattar et al., this issue). Four MPAs have been implemented in the atoll since 1999.

Input Data to Design a MPA Network for the Conservation of Coral Reef Biodiversity

Biodiversity was characterized by establishing species lists for 31 study sites: 29 benthic/fish sites, and two additional plankton sites (for hydrozoans). Rationales for site selections and specific taxonomic work are detailed elsewhere for each taxon (Andréfouët and Adam, this issue). In short, sites were selected to represent: 1) the different geomorphological and exposure strata (e.g. oceanic forereef, lagoonal, patch reef, forereef, etc.); 2) a range of coral cover, abundance, and growth forms, (reported by the initial AEC rapid surveys (Le Berre et al., 2009)) and; 3) spatial coverage (north to south, east to west).

For species data, the goal of the sampling strategy was to obtain the taxonomic composition of five different groups of taxa (macrophytes, coral, fish, hydrozoans, and other select invertebrates) in the same locations, thus providing a comprehensive multi-taxa list consistent across all sites. Despite the possible limitations related to the identification of some groups, such a dataset is unique. Indeed, taxonomic inventories generally include less biological groups (for example, fish and corals only), or groups that are sampled at different stations throughout the targeted area (e.g. Dalleau et al., 2010). Among the 29 benthic and fish sites sampled in Baa (Fig. 1), we only used the 18 sites where all taxa were surveyed.

The various taxa inventories yielded 178 species of macrophytes, 173 species of coral, 350 species of fish, 115 species of hydrozoans, 182 species of other selected invertebrates, for a total of 998 species combined on all 29 sites. On the 18 sites with exhaustive inventories, 941 species were recorded.

For habitat data, we used two different maps produced from Landsat satellite images at a spatial resolution of 30m, and Quickbird satellite images at a spatial resolution of 2.4m. Methods used to produce these maps are detailed in Andréfouët, Rilwan, Hamel (this issue). The Landsat derived habitat map contains 16 classes of geomorphological habitats. The Quickbird-derived habitat map contains 106 classes of habitats defined by information on: 1) geomorphology; and 2) benthic communities and structure.

All habitats maps (obtained from Landsat and Quickbird imagery) and species inventories were included into a database and into a Geographic Information System (GIS) project. Seven of the 16 habitats (44%) present in the Landsat-derived habitat maps were sampled, and 12 of the 106 habitats (11%) present in the Quickbird-derived habitat map have been sampled.

Mapping Biodiversity

To create a map of biodiversity for the entire atoll, we combined the point biological census data with the habitat maps. A list of species per habitat was compiled. Each habitat received, as associated species, all the species that were found in this habitat,

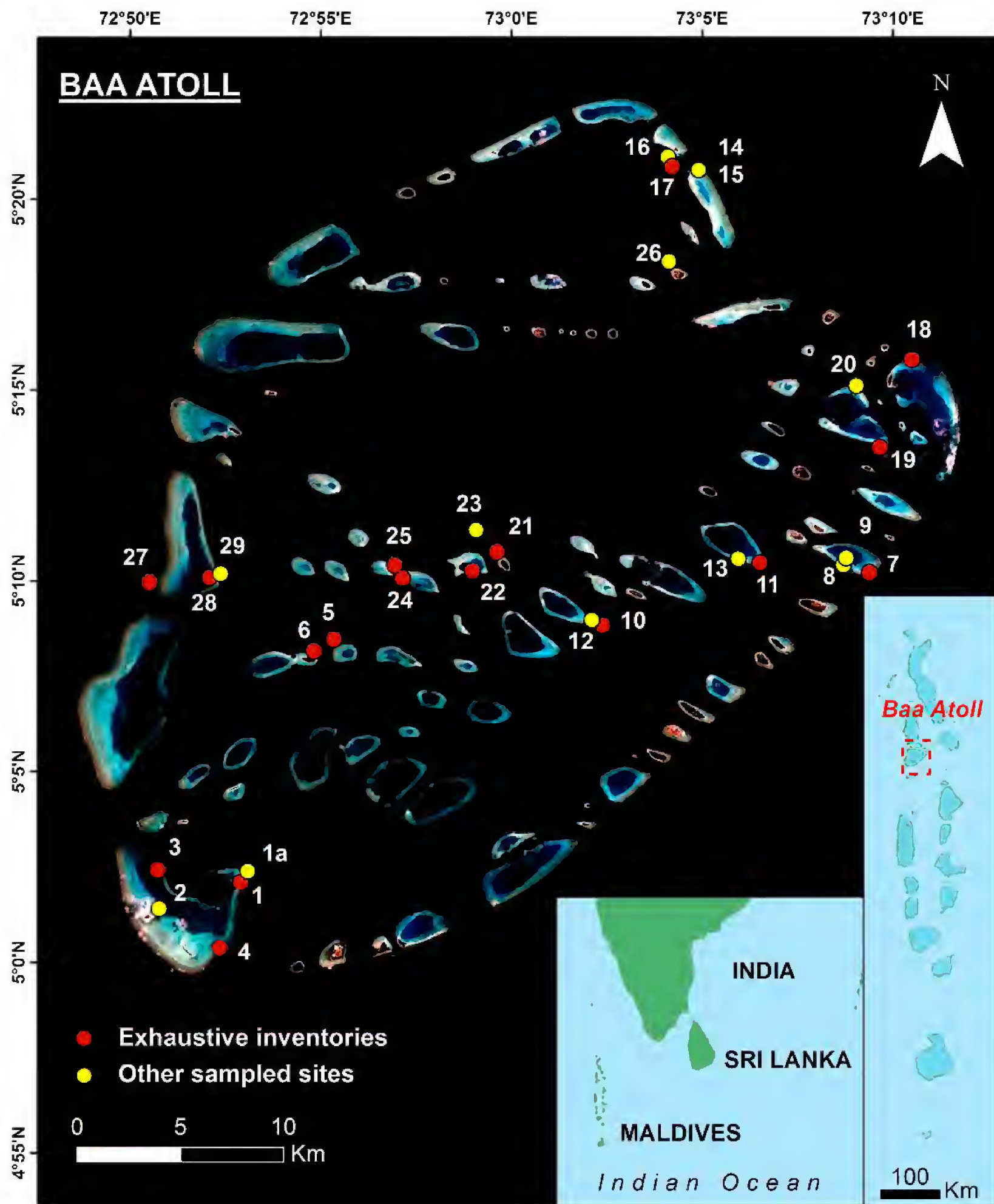


Figure 1. Location of Baa Atoll, Republic of Maldives in the Indian Ocean, and the sampling sites. Red circles correspond to the 18 sites where all taxa (macrophytes, coral, fish, hydrozoans and other select macro-invertebrates) have been inventoried. Yellow circles correspond to other sites that have been inventoried for only specific taxa, and thus for which a complete inventory is not available. Only fully surveyed sites have been used in the present study.

regardless of the location of the sampling site in the atoll. Baa Atoll was then partitioned into a grid of one by one kilometre cells covering the total mapped area. For each cell in both Landsat and Quickbird-derived habitat maps, we computed:

- 1) a list of the habitats present,
- 2) the habitat richness and,
- 3) a list of species per cell compiled from all habitats in the cell.

This three-step process is a straightforward way to generalize species distribution using habitat maps. We assumed that similar habitats in different atoll location would support similar assemblages of species, and thus similar amounts of biodiversity. This method is analogous to the process of creating species distribution or abundance maps from species records and mapped environmental predictors (e.g. via predictive models or geographic interpolation) (Jennings, 2000, Rodriguez et al., 2007, Choi et al., 2011). The difference in our method is that we used only one habitat map (either from Landsat or Quickbird imagery), itself the result of a variety of geological, environmental, ecological and climatic factors usually used to predict biodiversity patterns.

Selection of Conservation Units

To propose MPA locations, we used the gridded generalised map of biodiversity with the ConsNet software package (Ciarleglio et al., 2009). Our objective was to represent every single species at least a number of times x (representation target) in the proposed network while minimizing the number of selected cells. To assess sensitivity of the scenarios to the representation target, we chose to generate solutions for three different threshold of representation (x). In other words, if $x=1$, we sought at least one representation of each single species in the conservation network. We created scenarios for $x=1$, 5 and 10.

The use of heuristic solutions allows a fast exploration of the solution domain, and provides starting points for an exhaustive search. This strategy was adapted to our conservation objective because the ConsNet heuristics is constrained by the ‘Minimum Area Problem’, i.e. selecting the fewest cells possible meeting the representation target. The ‘Minimum Area Problem’ conservation constraint (or ‘objective’ in ConsNet) has several advantages: it is widely used and easy to understand and set up, it has an excellent ability to drive search, and it has no potential for failure (Ciarleglio et al., 2009).

Heuristic solutions were created with three different algorithms (for details, see Ciarleglio et al., 2009). In our case, for each algorithm, the surrogates of overall biodiversity correspond to the recorded species in all taxa.

- 1) The ‘Most Deficient Surrogates’ (MDS) complementarity algorithm adds cells to the network that reduce the most the remaining deficits. When all targets are met, the deficit is null.
- 2) The ‘Rarity First’ (RF) algorithm adds cells that contain the rarest species which have not yet met the representation target.
- 3) The ‘InterLeaves’ (ILV) algorithm adds cells with the rarest and most deficient species.

Extended search for best solutions also used the ‘Minimum Area Problem’.

No constraint on the redundancy of cells in the network was requested. Importantly, no minimum area or maximum cost constraints have been implemented, in contrast to theoretical recommendation for conservation planning when resources are limited. Here, this was not necessary, as the goal is to propose MPA solutions based on biodiversity, without further clear specifications from AEC to use any cost function. Nevertheless, we chose to take into account the compactness of the network (i.e. we promoted the selection of few large MPAs instead of many small MPAs) to propose networks of MPAs that would be logistically easier to manage.

RESULTS

Distribution of Species Richness

On the 18 sites where there was a complete inventory of all taxa (Fig. 2), there were between 214 and 301 species per station, and an overall total of 941 species.

The generalisation of species distribution from Landsat-derived habitat maps provided 1199/1234 cells with species information (97%). The generalisation of species distribution from Quickbird-derived habitat maps provided 469/1219 cells with species information (38%) (Fig. 3). Such differences in the generalisation results were expected given the differences between each mapping product. The results of the generalisation process are driven by the habitat associated to the sampling station, as well the number of habitats contained in a cell.

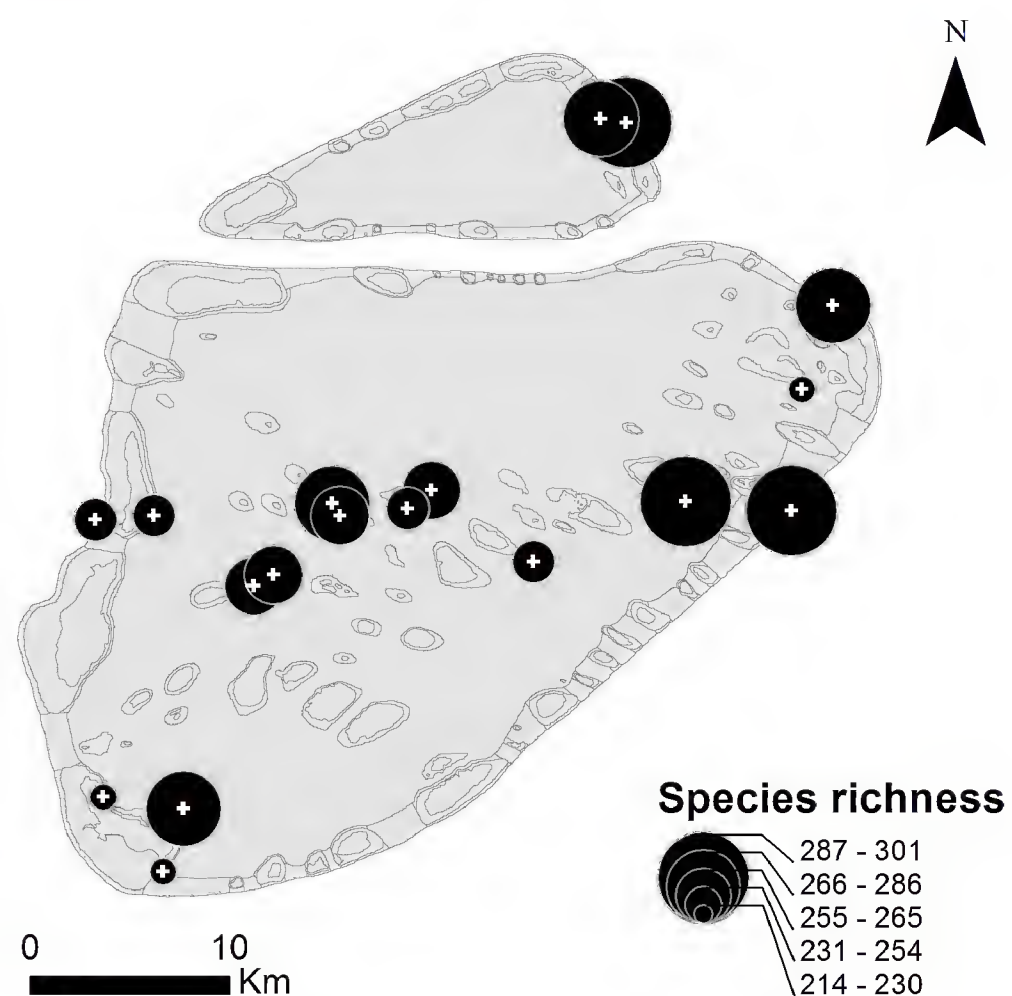


Figure 2. Variation of species richness for the 18 sampled sites where a comprehensive inventory of macrophytes, coral, fish, hydrozoans and other select invertebrates was available. Differences in species richness are small. Thus to ease visualization, species richness among sites is represented in five circle sizes, each corresponding to a class of richness (from 214 to 301 species) obtained with Jenks natural breaks classification method. The grey background map is the habitat map derived from Landsat imagery.

The most striking differences were for deep lagoon areas. With Landsat imagery, a number of small geomorphological units below 10 meter depth (pinnacles, etc.) could not be mapped and were thus part of the ‘Deep Lagoon’ class. Several census stations were thus included in the Deep Lagoon class, and the Deep Lagoon class were allocated the species from these stations. Conversely, with Quickbird, these small units could always be mapped individually, and assigned to other classes of habitats than ‘Deep Lagoon’. Thus, the Quickbird derived habitat map offered no species information for a much larger deep area than the Landsat map (Fig. 3). When species richness could not be estimated,

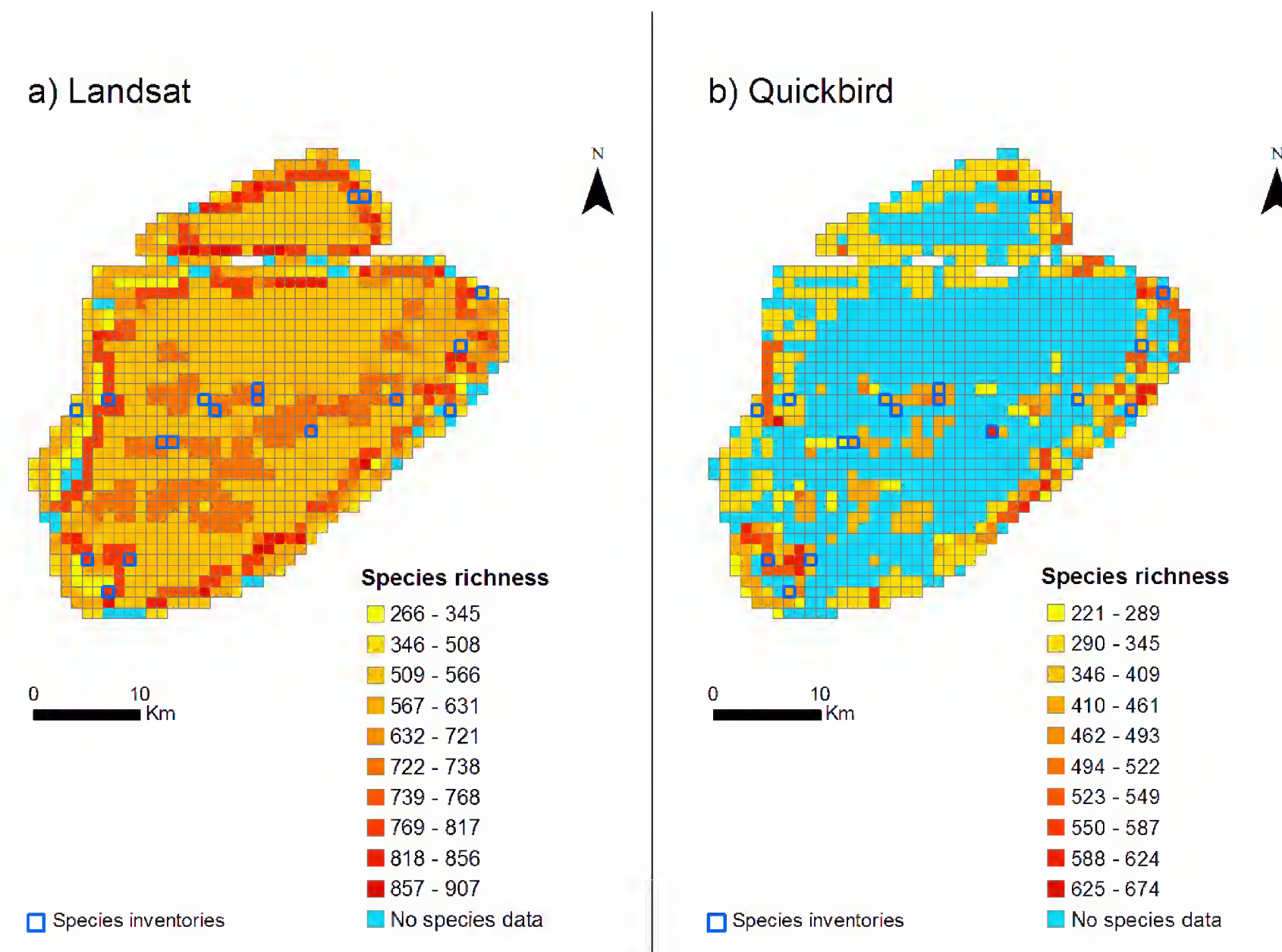


Figure 3. Spatial distribution of the estimated species richness for Baa Atoll (see text for details on the creation of these products). Blue cells remain virtually void of species because there is no species information for the habitats they contained, i.e. none of the sampled stations were located on those habitats. Cells with a dark blue border correspond to the conservation units which have been inventoried, i.e. cells we used as a basis for the generalisation procedure.

the cells remained void of species and were not included in the MPA planning process. Identification of Conservation Areas Networks (CAN)

The ConsNet software returned several ‘best’ solutions for the planning of MPA networks in Baa Atoll that were quite different. The algorithm easily reached the conservation objectives, i.e. it reached the target for each species recorded, in the minimum number of cells possible. The examples shown in Fig. 4 are a sample of all possible designs for the same dataset and conservation objectives, but there are many other solutions.

As expected, the use of generalisations from Quickbird maps returned larger CANs than when using species richness maps from a Landsat habitat classification. If the objective was to represent every species at least once in the CAN, the algorithm proposed protection of two sites using the generalisation based on Landsat imagery, against six with the Quickbird generalisation. With a 10 species target, the use of the Landsat generalisation generated a 24-cell CAN, including two of the sampled sites. With the Quickbird map, 70 cells were selected, including five of the sampled sites.

DISCUSSION

The aim of this study was to provide AEC and Maldivian stakeholders involved in the conservation of Baa Atoll biodiversity with an objective layer to identify sites that deserve adequate conservation. We based our analyses and site selection on clear and quantitative biodiversity criteria.

Although this seems to be a fairly simple and straightforward process, despite an abundant literature on MPAs and conservation planning, there is surprisingly little other similar studies available for a coral reef environment, and none for atolls. Conservation planning tools have been used in ‘the real world’ (i.e., with the participation of local stakeholders and governmental agencies), for instance for the Great Barrier Reef in Australia (Fernandes et al., 2005) and for the coastal reef systems of Kimbe Bay in Papua New Guinea (Green et al., 2009). Atoll systems within the Phoenix Islands Protected Area in Kiribati have been recently declared protected areas and World Heritage Areas, but entire atolls were included, without spatial analysis. Biodiversity-driven conservation planning examples appear to remain limited. We expected that conservation planning driven by biological data would be frequent, but this is not the case. It may be that such studies remain technical and are not published in peer reviewed journals, but our experience in developing and developed countries suggest that there are likely no plethora of hidden gems. Ongoing planning often prioritizes socio-economic information, and biological information is often utilised as secondary decision-support layers.

The trend in the scientific literature is to propose increasingly complex theoretical schemes that account for processes that are poorly characterized worldwide, such as climate change effects, maintenance of reef resilience, meta-population connectivity and so forth. These remain only interesting theoretical exercises. They cannot be implemented in most places, and are of doubtful practical value in the real management world given the necessity of prompt action.

Conceptually and methodologically, the present study is straightforward. It provides simple guidelines that can be replicated elsewhere with adequate expertise (i.e., taxonomic knowledge, habitat mapping, and conservation planning software). It is a simplification of recommended theoretical conservation schemes, as neither socio-economic drivers nor important ecological processes (e.g., connectivity) are taken into account in our design. Given the lack of adequate knowledge of these processes, that will take years to be acquired, our immediate goal was to create a biodiversity-based recommendation layer. It has to be used in conjunction with other key constraints before

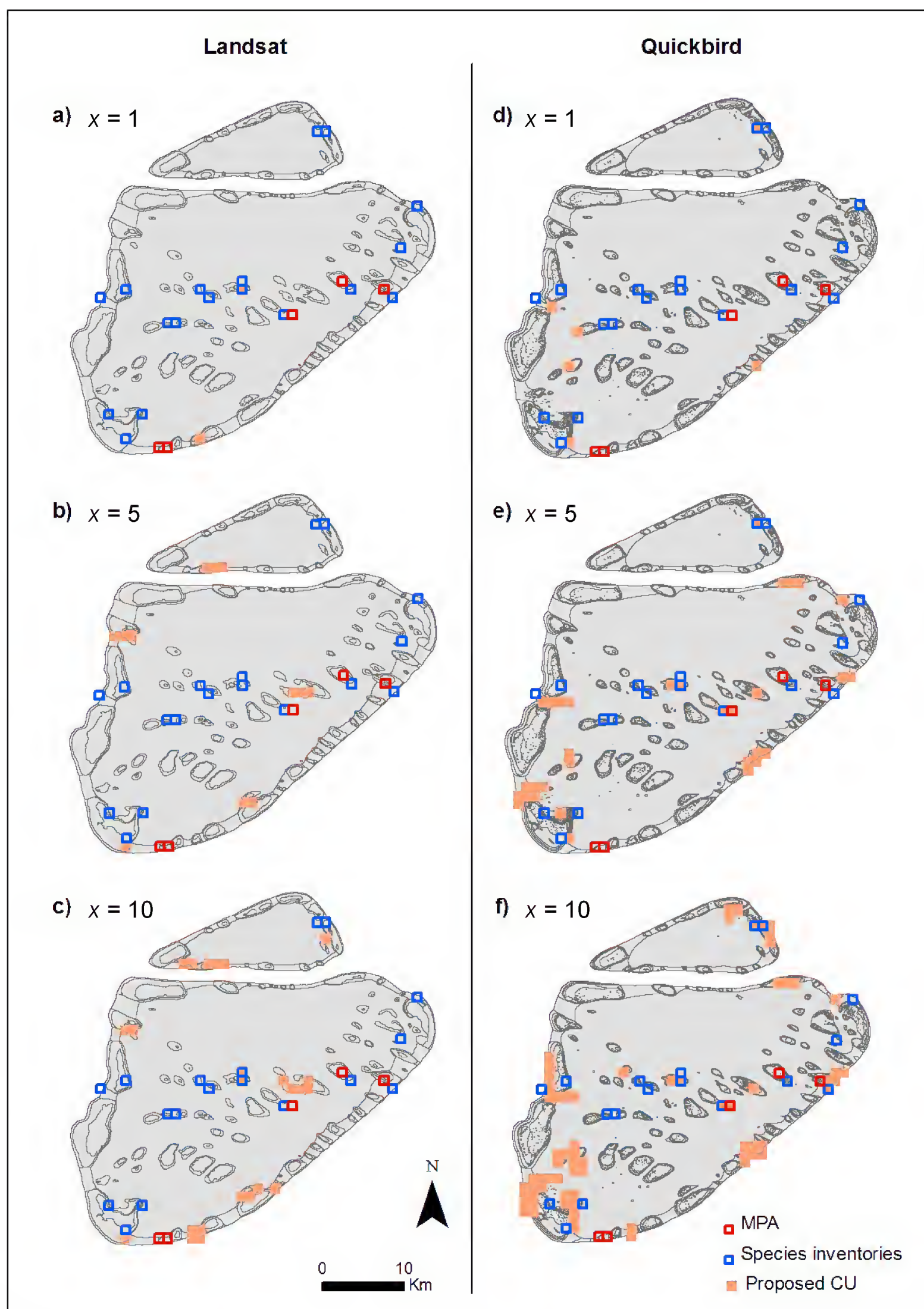


Figure 4. Proposed Conservation Units (CU) in Baa Atoll obtained with the ConsNet software from the generalised maps of species richness. Each map is one example out of the many best solutions for MPAs networks generated by the software for the same conservation objectives. From top to bottom, objectives were to include in the network a) and d) all recorded species at least once; b) and e) all species at least five times; and c) and f) all species at least 10 times.

reaching a final decision. Final decisions regarding the proposed network of MPAs should eventually be made using the full range of knowledge available, especially socio-economic characteristics.

From the various solutions available, the MPA network that we recommend for further consideration is presented in Fig. 4, f (see Fig. 5 for a map combined with additional AEC data). We selected the output presented in Fig. 5 primarily because it encompasses current existing MPAs, and includes a number of sampling sites, thus minimizing the uncertainty that could arise from the generalisation of species distribution using habitats. Seven MPAs have been implemented on Baa Atoll since 1999. Dhigalhi Haa, a famous site for sighting marine megafauna, was declared protected in 1999; Olhugiri Island and its house reef were declared protected in 2006 for its unique vegetation and fertile soil; and Agafaru, a popular dive site, was declared protected in 2009 as was Hanifaru, a now famous feeding aggregation site for whale sharks and manta rays. Earlier this year, five more protected areas were declared in Baa Atoll, including the increase in boundaries of two existing protected areas, Hanifaru and Dhigali Haa. The three new protected areas created in 2011 are Bathalaa region, Maahuruvalhi faru, and Mendhoo region.

The proposed network includes portions of five of the seven existing MPAs (see proposed MPAs 1, 2, 5, 7, 8 and 14 in Fig. 5), two sea turtle nesting sites (MPAs 2 and 10) and the two unprotected bird nesting sites (MPAs 2 and 12). It also includes a number of popular dive spots. Several MPAs are close to resort islands, thus likely making them more attractive and of higher value for visitors due to nearby areas with recognized biodiversity value and protective status (Roberts et al., 2001). As a consequence, it is expected that the proposed network will be more easily accepted by AEC and local stakeholders, who already have been through a number of meetings, discussions and negotiations to select these sites. The fact that several sampling sites are included in the network also offers a strong baseline for future monitoring of species diversity. Additional sampling efforts could also quantify how much was missed in the initial surveys.

Inherent limitations to the approach we followed here are mainly related to the intrinsic limitations of the datasets related to species identification within each taxa and of each habitat map. The financial resources available for the project allowed for sampling 29 sites, 18 multi-taxa sites, and five major taxonomic groups to do in the course of the three weeks survey. Increased sampling efforts may likely change the output, especially if other taxa are included.

As Baa Atoll is an oceanic atoll, the diversity of habitats is low, compared to systems with a well defined land-outer reef gradients (e.g. Wallis Island in Dalleau et al., 2010). The small inherent habitat richness in an atoll, distributed fairly evenly throughout the atoll, added to the spatial scale we chose (one by one kilometre cells) does not lead to well defined spatial patterns. This explains why MPA solutions can spatially be quite different from one scenario to another.

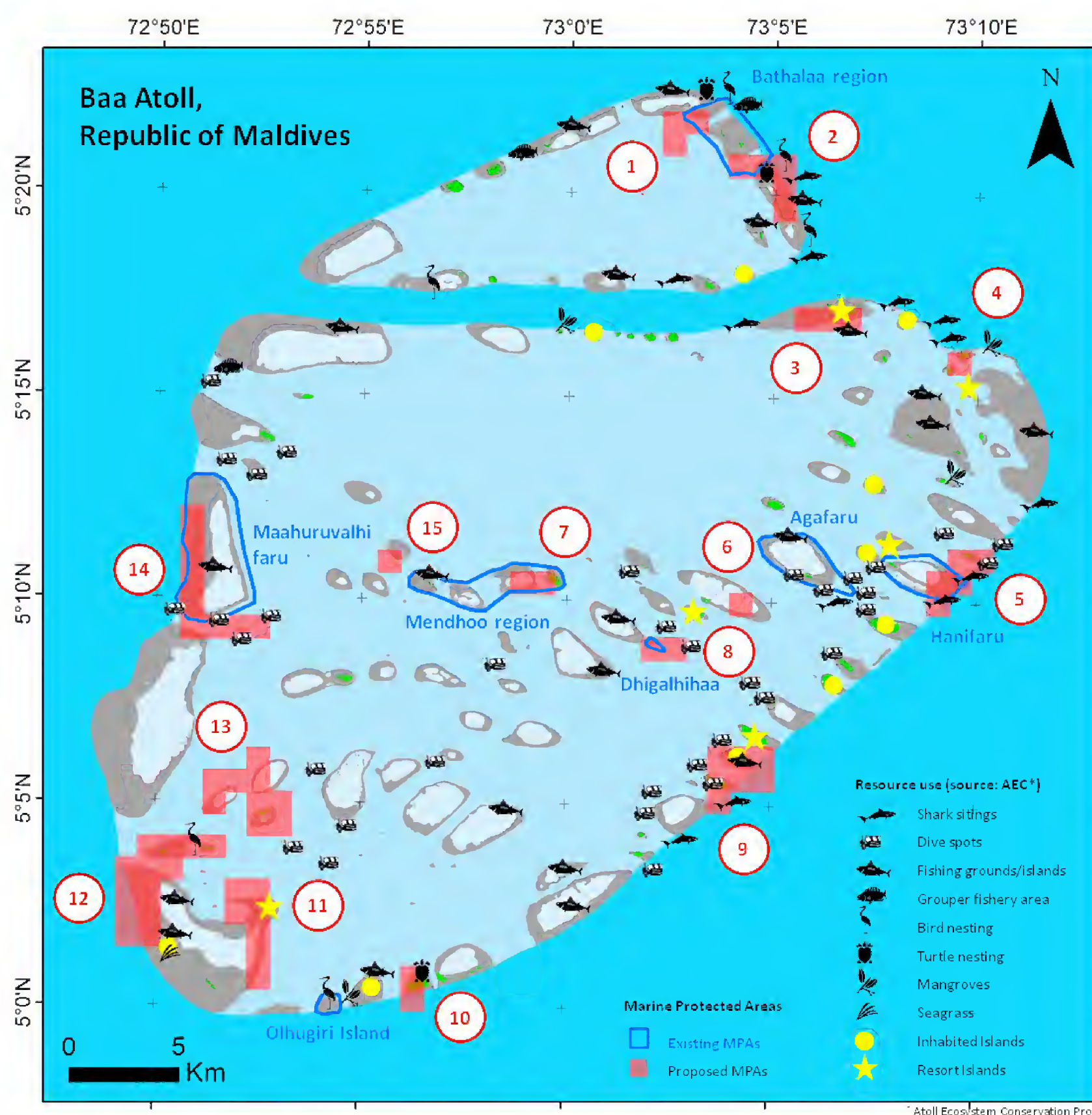


Figure 5. One of the proposed MPA networks (orange cells), overlapped with resource use information (black and yellow pictograms) extracted from a map provided by the Atoll Ecosystem Conservation Project (available to download at <http://www.biodiversity.mv>). Each number corresponds to a MPA contained in the network. In this case, the conservation objectives were defined to represent every recorded species at least 10 times in all combined conservation units (CU), within the smallest number of CUs, and taking account of the compactness of the network. The input species data were extracted from the generalised species map, obtained with a habitat map from Quickbird imagery and with the comprehensive biological inventories.

CONCLUSION

The conservation area networks proposed here offer to the Atoll Ecosystem Conservation project an objective basis to implement conservation decisions. The proposed network was built using a spatially-explicit consistent dataset, which allowed mapping of Baa coral reef biodiversity. This effort complements the previous AEC rapid assessment, that provided substantial information on other aspects of Baa unique

environment such as mega-fauna or coral cover. The CAN shown in Fig. 5 is thus one of the many necessary milestones in a dynamic process aiming for long term conservation of Baa Atoll. Real world conservation network implementation is a long-term process requiring a wide range of data types and clear objectives to be able to move forward. This study brought a necessary biodiversity dataset to contribute to the process. We suggest that similar studies need to be conducted elsewhere to initiate the conservation planning process, especially when the biological system is poorly known. Even if ultimate recommendations and decisions may need to be based on socio-economic drivers and criteria, there is no doubt that the availability of such a biodiversity-based plan for conservation legitimates the process of decision making.

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